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Adaptation of Ultrasonic Doppler Velocimetry (UDV) to Measurement of Lead-Bismuth Flows

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The ultrasonic Doppler velocimetry (UDV) has become a technique of preference in the measurement of flow velocity in liquid metals[1][2][3][4]. The principle of the UDV method is to use the pulsed echo technique of ultrasound and to detect the position shifts via the reflected wave from trace particles or density variations in the moving fluid. Position information is obtained by measuring the time of flight in transmission and reflection. This ability to measure a full velocity profile along the ultrasonic (US) beam in real time, as well as to work in opaque fluids in a non-intrusive way are the main advantages compared to other techniques[4].

This report summarizes the working principles of UDV, the selection of US probe parameters, the coupling and transmission of US through container wall into fluids, and the reported experience in the literatures. It will establish the needs, the requirements and a technical path forward for the LBE technology development.

Working Principles of UDV[5]

“The term ‘Doppler ultrasound velocimetry’ implies that the velocity is measured by finding the Doppler frequency in the received signal, as it is the case in Laser Doppler velocimetry. In fact, in ultrasonic pulsed Doppler velocimetry, this is never the case. Velocities are derived from shifts in positions between pulses, and the Doppler effect plays a minor role. Unfortunately, many publications, even recent ones, fail to make the distinction, resulting in erroneous system description and fallacious interpretation of the influence from various physical effects.”[5]

In pulsed Doppler ultrasound, a transducer periodically sends short US bursts and continuously receives echoes from impinged targets in the US beam path. By measuring the time delay between an emitted burst and the echo (usually through the measurement of the phase shift), the target velocity is calculated by

$$v = \frac{c \cdot \delta}{2 \cdot f_e \cdot \cos\theta \cdot 2\pi T_{prf}} = \frac{c \cdot f_d}{2 \cdot f_e \cdot \cos\theta}, \tag{1}$$

where f_e is the emitting frequency, $\delta = 2\pi f_e (T_2 - T_1)$, f_d is the delay frequency $(1/(T_2-T_1))$, θ is the angle between the US beam and the target trajectory (flow direction). T_{prf} is the pulse repetition time interval.

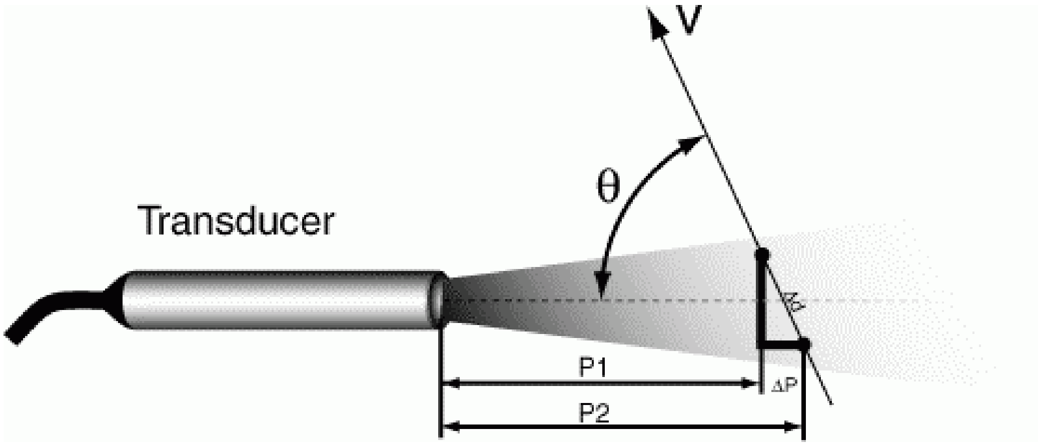

Figure 1. Schematic illustration of the configuration for calculating velocity from US signals[5].

Because the information is obtained periodically, it is limited by the Nyquist theorem. A maximal velocity exists for each pulse repetition frequency (Prf) – corresponding to a phase shift $\delta_{\max} = \pi$:

$$v_{\max} = \frac{c}{4 \cdot T_{prf} \cdot f_e \cdot \cos\theta}. \quad \textbf{(2)}$$

Higher velocity targets will produce aliased signals and get folded under the above limit.

In addition to the velocity limitation, there is a limitation in depth. The ultrasonic burst travels in the liquid at a velocity that depends on the physical properties of the liquid. The pulse repetition frequency gives the maximum time allowed for the burst to travel to the particle and back to the transducer. This gives a maximum depth of:

$$P_{\max} = \frac{T_{prf} \cdot c}{2}. \quad \textbf{(3)}$$

From the above two equations, we observe that increasing the time between pulses (T_{prf}) will increase the maximum measurable depth, but will also reduce the maximum velocity that can be measured.

The US waves from the transducers are reflected or scattered upon impinging particles or density variations that have different acoustic impedance with the liquid. The acoustic impedance is $Z = \rho\, c$ (c is the sound velocity, ρ the density).

If the size of the particle is larger than the wavelength, the US waves are reflected and refracted. If the size of the particle is much smaller than the wavelength, the US waves are scattered in all directions. UDV utilizes scattered US waves, therefore needs small particles. In oxygen controlled LBE systems, the small amount of dissolved/dispersed oxides in LBE may be sufficient as scattering targets.

Selection of US Probe Parameters

We need to carefully select the US probe parameters for the range of velocities to be measured, the spatial dimension of the measurement volume and the required spatial resolution.

The previous section discusses the limits of the velocity and depth. For the typically available emitting frequencies and Prf on the UDV instruments available, the following tables give the parameter selections (the sound velocity in LBE is approximated by that in pure solid Pb, c = 2240 m/s):

v_{max} [m/s] / T_{prf} [μs] / f_e [MHz]	64	128	256	512	1024	2048
1	12.37	6.19	3.09	1.55	0.77	0.39
2	6.19	3.09	1.55	0.77	0.39	0.19
4	3.09	1.55	0.77	0.39	0.19	0.10
8	1.55	0.77	0.39	0.19	0.10	0.05

Table 1. Maximal velocity measured UDV.

T_{prf} [μs]	64	128	256	512	1024	2048
P_{max} [m]	0.072	0.143	0.287	0.573	1.147	2.294

Table 2. Maximal depth for unaliased UDV measurement.

From Table 1and Table 2, it can concluded that for measuring LBE flow in pipes of 2" diameter, and of velocity up to 2 – 3 m/s, the 2, 4 and 8 MHz probes, with T_{prf} in the range of 64 – 1024 μs are optimal.

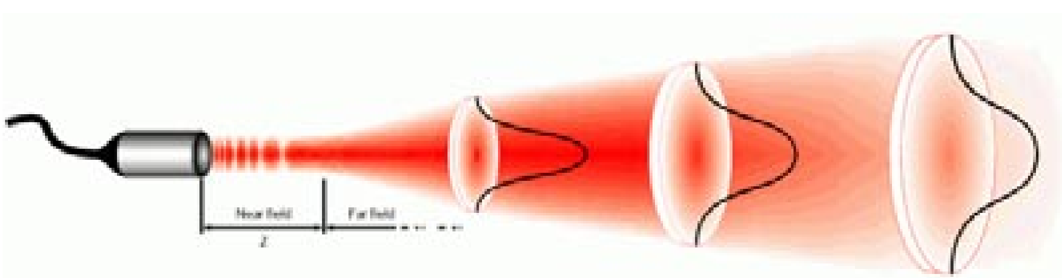

Figure 2. A US transducer's acoustic field[5].

The US beam behaves differently in the near and far field (
Figure **2**). In the near field, the acoustic field is nearly cylindrical, with a diameter slightly less than the emitter's diameter D. The depth of the near field is $z = D^2/4\lambda$.

In the far field the US beam diverges. The half angle $\delta = \arcsin(1.22\ \lambda/D)$. A compromise must be established between λ and D to achieve the thinnest beam at the desired depth. For c = 2240 m/s in LBE, the half angles are (D = 0.8 cm):

f_e [MHz]	1	2	4	8
z [cm]	0.71	1.43	2.86	5.71
δ [^{o}]	19.97	9.83	4.90	2.45

Table 3. Near field depth and half angle of far field divergence for various emitting frequencies (D = 0.8 cm).

Coupling of Probes and Transmission of US

There are several critical issues in the coupling of probes and transmission of US. They include the wetting of the contact interface with the liquid metals, the extension of the probes to accommodate the upper temperature limit of the transducers and the high working temperature of the liquid metals, the reduction of transmission loss and the preservation of mono-mode acoustic propagation through the extension.

In the measurement of sodium flow, it is reported necessary to remove the oxide layer from the steel surface to guarantee a sufficient transmission of US energy from the adapter into the flow [4]. Both chemical and mechanical treatments are used, and the test section is heated for some time to ensure wetting.

In LBE systems, oxygen is controlled to form a protective oxide on the steel surface to mitigate the rather severe corrosion problem. Removal of the oxide may not be practical. Raising the temperature to above 400^{o}C (or a threshold to be determined in wetting experiments) for a prolonged period may be necessary. The UDV instrumentation has the function feature to measure the reflected power, and can be used to determine the optimal treatment procedures experimentally.

The conventional piezoelectric transducers using PZT are restricted to sustained working temperature of 150^{o}C and short-term temperature of 200^{o}C. Some piezoelectric materials with higher Curie temperatures have significant loss of the piezoelectric properties and low coupling factors that render them ineffective, since UDV sensors require relatively high signal-to-noise ratio.

To be able to use the conventional transducers for LBE flows at high temperatures, a mechanism is needed to extend the adapter so that the contact temperature at the location of the transducers is below the upper limit for the probes. It is thus necessary to study the reduction of transmission and maintenance of mono-mode propagation to preserve the signals through the extensions.

Transmission of a US Beam through a Planar Adapter[4]

To isolate the US probe from the chemical attack by LBE, a steel adapter interface is needed. The interface should be planar to allow the incidence and reflection of the US wave perpendicular to the interface. The thickness of the interface should allow maximal transmission of the US wave. The transmission coefficient is given by[6]:

$$D_{plate} = \frac{1}{\sqrt{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 \frac{2\pi d}{\lambda}}}, \tag{4}$$

where $m = Z_{\mathrm{LBE}}/Z_{\mathrm{st}}$ is the ratio of the acoustic impedance between liquid LBE and steel, d is the thickness of the plate and λ is the wavelength in the plate material. $Z_{\mathrm{LBE}} = 24\mathrm{x}10^6$ Ns/m^3, $Z_{\mathrm{st}} = 45\mathrm{x}10^6$ Ns/m^3(c = 5720 m/s). The most commonly used acoustic coupling medium, silicon grease, has $Z_{\mathrm{gr}} = 1\mathrm{x}10^6$ Ns/m^3 that is grossly mismatched with that of steel and LBE. In practice, the probe and the adapter should be tightly squeezed together to minimize the thickness of silicon grease in between them.

The LBE and stainless steel is slightly mismatched in terms of acoustic impedance. So the transmission of a US beam through a steel plate undulates with the plate thickness. The reduction can be nearly 17% (Figure 3) when the plate thickness mismatches the wavelength. For maximal transmission, the plate thickness should be multiples of the half wavelength.

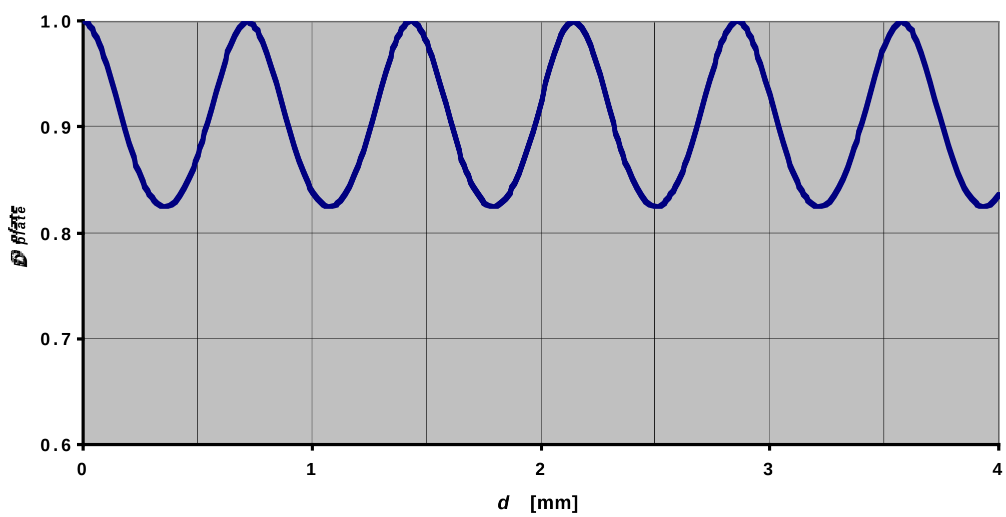

Figure 3. Transmission coefficient of a US beam through a stainless steel plate into LBE.

Mono-mode Transmission of a US Beam through an Extension Adapter[7]

For higher LBE temperatures, the extension adapter has to be long enough to allow for heat dissipation and temperature decrease before contact with the US probe. For measurements of the Doppler signals a dispersionless US wave propagation is required. This results in a restriction of the thickness d of the extension adapter[8]

$$\frac{d \cdot f}{c} < 0.1. \qquad (5)$$

The sound velocity *c* for steel is about 5720 m/s, leading to *d* < 0.143mm.

Adaptation of UDV to LBE Flows

The foregoing discussion has established the feasibility and parameters for using UDV in LBE flows. It has been demonstrated experimentally at FZR and FZK[7][9]. The LANL effort should be built upon such successes. The following is a planned path forward.

We currently have a DOP1000, Model 1032 ultrasonic velocimeter made by Signal-Processing SA (Lausanne, Switzerland), and two high temperature series probes, TR0208LH, 2 MHz, 8mm diameter, and TR0408LH, 4 MHz, 8mm diameter. According to the earlier discussion, they are well suited for UDV measurement of LBE flow.

The LBE materials and thermal hydraulic test loop, DELTA, has been operational and has oxygen monitoring and control functions built in. The loop also has several removable sections that can be used to implement UDV probes and adapters.

The first step is to fabricate a 316L adapter with a 2.14 mm thick planar interface, 8.1mm inner diameter, 10 cm long, welded into the UDV section of 2” schedule 40 316L pipe. The angle between the axis of the adapter and the pipe is 45^o. The pipe section is then installed at the location outside of the discharge exit from the sump tank.

At the operating temperature of 180^{o}C, use silicon grease to couple the US probe to the planar interface of the adapter to measure the LBE flow profile inside the pipe. Vary the pump speed to change the flow rate. Vary the oxygen concentration from near saturation downward, and map the reflection signal strength to help select the optimal measurement conditions.

The next step is to fabricate the extension adapter, called a wave guide[7], by rolling up 0.1 mm thick and 200 mm long stainless steel foil around a capillary tube. The front and back ends are stainless discs, 0.142 mm thick, welded to the coil. This will be used to couple the US probe to the existing planar adapter with silicon grease. This step should be taken with consultation of the FZR researchers. If international collaboration can be established and funding is available, an integrated US probe with a wave guide adapter may be obtained from FZR.

The DELTA Loop operating temperature can then be raised to 350 – 400^{o}C for measurement of LBE flow at near prototypic operating conditions. Vary the LBE flow rate and oxygen concentration to help determine the optimal UDV measurement conditions.

Eventually, the UDV technique should be adapted and developed for two kinds of applications. On the R&D side, UDV will be applied in the design and study of flow fields in technologically relevant configurations, such as in flow distribution manifolds, reactor cores, and spallation targets. On the deployment side, UDV will help enhance the ISI (in-service inspection) capabilities that are lacking for liquid metal systems.

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